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Multi-objective optimization of a mixed renewable system with demand-side management

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ABSTRACT

The 2001/77/CE European Commission Directive sets the target of 22% of gross electricity generation from renewables for the Europe, by 2010. In a scenario of large scale penetration of renewable production from wind and other intermittent resources, it is fundamental that the electric system has appropriate means to compensate the effects of the variability and randomness of the wind, solar and hydro power availability. The paper proposes a novel multi-objective method to optimize the mix of the renewable system maximizing its contribution to the peak load, while minimizing the combined intermittence, at a minimum cost. In such model the contribution of the large-scale demand-side management and demand response technologies are also considered.

Contents

1. Introduction

The 2001/77/CE European Commission Directive sets the target of 22% of gross electricity generation from renewables for the Europe, by 2010. In the case of Portugal the target is more ambitious at 39%. In order to satisfy this target, it is planned the installation of additional generation capacity from renewable sources, in which the largest part of the increase it is in wind power, whose target is to reach 5700 MW by 2012, and 8000 MW by 2020.

In a scenario of large scale penetration of renewable production from wind and other intermittent resources, it is fundamental that the electric system have appropriate means to compensate the effects of the variability and randomness of the wind power availability. Portugal has a relatively large hydro capacity of 4600 MW and only about 50% of the potential is used. Large solar photovoltaic plants have been installed and are planned. The

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foreseen sharply decreasing costs will allow a large increase of the solar capacity in the next 10–15 years. To ensure an optimal mix in the medium-term, three main renewable sources (hydro, wind and solar) deserve to be considered. Also, through the proper application of demand-side management (DSM) and demand response (DR) technologies it is possible to influence the load shape to mitigate the unbalance between intermittent power and the demand.

2. Wind power intermittence

Wind energy has characteristics that differ from conventional energy sources. If the contribution of this production vector in energy terms is not a cause of concern, the contribution to the power balance, and therefore the impact in the supply security needs attention due to the intermittent and random character of this production option.

The output of wind power is driven by environmental conditions outside the control of the generators or the system operators. Since the wind is determined by random meteorological processes it is inherently variable. Supply of power from wind turbines is stochastic in nature and the actual power is more or less proportional to the third power of the wind velocity (from cut-in wind speed to the rated wind speed). The wind output varies seasonally between summer and winter [1] and the variations are also present on shorter time scales, namely on hourly basis [2]. Unlike conventional capacity, wind-generated electricity cannot be reliably dispatched or perfectly forecasted, and exhibits significant temporal variability.

Several extreme ramp rates were recorded during storms [3]:

- Denmark—2000 MW (83% of capacity) decrease in 6 h or 12 MW (0.5% of capacity) in a minute on 8th January 2005.
- North Germany—over 4000 MW (58% of capacity) decrease within 10 h, extreme negative ramp rate of 16 MW/min (0.2% of capacity) on 24th December 2004.
- Ireland—63 MW in 15 min (approx 12% of capacity at the time), 144 MW in 1 h (approx 29% of capacity) and 338 MW in 12 h (approx 68% of capacity).
- Portugal—700 MW (60% of capacity) decrease in 8 h on 1st June 2006.
- Spain—800 MW (7%) increase in 45 min (ramp rate of 1067 MW/h, 9% of capacity), and 1000 MW (9%) decrease in 1 h and 45 min (ramp rate −570 MW/h, 5% of capacity). Generated wind power between 25 and 8375 MW have occurred (0.2% and 72% of capacity) in a single year.
- Texas, USA—loss of 1550 MW of wind capacity at the rate of approximately 600 MW/h over a 2.5 h period on 24th February 2007.

In addition to being variable, wind power production is also a challenge to accurately predict on the time scales of interest to: day ahead and for long-term planning of system adequacy. It is possible to forecast in a concrete zone, the average wind power density for the whole year; however, it is impossible to precisely forecast the days or the hours with wind [4].

Integrating large amounts of wind energy into the electric generation mix requires some special considerations. Beyond the variability, a lot of wind generation occurs in hours when energy use is low. The uncontrollable nature of wind makes it less valuable to system operators than dispatchable power. The variability and uncertainty of wind energy production require that power system operators take measures to manage its delivery. These measures may increase the cost incurred to balance the system and maintain reliability. Substantial amounts of wind generation in a utility system can increase the demand for the various ancillary services. Previous results also reveal a diminishing benefit as wind power penetration increases [5].

In 2005, the impact of meeting 100% of Western Denmark's annual electrical energy requirement from wind energy was analyzed [6]. The results of the study demonstrated that the system could absorb about 30% energy from wind without any wasted production. However when wind share reaches 50% the excess wind energy starts to grow considerably. With the hypothesis of total energy demand of 26 terawatt-hours (TWh) generated by wind power, 8 TWh of the wind generation would be surplus because it would be generated during periods of low consumption. In that case, the electricity costs would double, because of the need to use other costlier back-up systems.

3. Options for managing intermittency

The connection of wind turbines to the electricity grid can potentially affect supply reliability and power quality, due to the unpredictable fluctuations in wind power output [7]. In a scenario of large scale penetration of renewable production from wind and other intermittent resources, it is essential that the electric system have appropriate means to compensate the effects of the variability and randomness of the renewable power availability. This concern was traditionally addressed by the promotion of the wind resource studies and by the identification of solutions based on reversible hydropower dams [8]. However, in the electric system planning, other options deserve to be evaluated.

The intermittency of wind energy can be reduced by some techniques:

- Grid integration.
- Technical distribution of the generators.
- Geographic distribution of the generators.
- Improved forecasting techniques.

These techniques have as aim the increasing of the predictability of the production and the substantial reduction of the global variations. However, although those improvements bring benefits, several periods of low wind production and substantial variations will remain. Thus tools to respond to short- to medium-term and long-term variability will be necessary, managing the operational and capacity reserve, respectively. For large scale integration of wind power the provision of flexible capacity reserve will be of crucial importance. To achieve that aim several options are possible:

- Power plants providing operational and capacity reserve.
- Interconnection with other grid systems.
- Curtailment of intermittent technology.
- Dispatchable distributed generation.
- Energy storage.
- Use of complementarily between renewable sources.
- Demand-side management.
- Demand-side response.

All these options have as aim continuously balancing demand and supply and backing up other capacity shortage. The present paper analyses the application of the three last methodologies in Portugal.

4. Complementarity between renewable sources

To evaluate the intermittence and complementarity from renewable energy production, a climate data time series over 50 years was obtained. The collected information includes the global solar radiation (monthly average), the wind velocity (monthly

average) and the monthly water inflow in dams. The locations for data collection were selected based on the approximation between the collected data and the annual variation of the wind power, solar photovoltaic and hydropower in all the country.

4.1. Multi-variable climate model

With the collected data, a mathematical model was developed, to generate random years, enabling the study of the sources complementarity for a large number of years. The variable with lesser deviation from a regular pattern (daily and seasonal cycles) is the solar radiation and thus was tacked as the base variable for the model. As it can be observed in Fig. 1, the collected data has a distribution close to a normal distribution, and thus the solar radiation was generated randomly with the Box–Müller transformation (1)

$$S_{mx} = \mu_{Sx} + \sigma_{Sx}\sqrt{-2\ln U_1}\sin(2\pi U_2) \quad (1)$$

where: S_{mx} is the solar radiation of the model (month x); μ_{Sx} the average value of the solar radiation (month x); σ_{Sx} the standard deviation of the solar radiation (month x); U_1 and U_2 is the independent values randomly generated by a uniform distribution, between 0 and 1.

The wind velocity is more uncertain than the solar radiation, but more predictable than the water inflow, and thus was then considered as secondary variable in the model. However, wind speed cannot be determined purely by a random distribution, because the two variables are not independent. But since a perfect correlation does not exist, it is incorrect to determine the wind velocity only with the correlation with solar radiation. Thus, wind velocity was determined with two components: random component and component obtained with the wind-solar correlation.

The wind speed probability density function follows a Weibull distribution, but the monthly values variation (from year to year) also follows a pattern similar to a normal distribution (Fig. 2). Therefore the first component was randomly generated by the same process that was used to the solar radiation (2).

$$W_{rx} = \mu_{Wx} + \sigma_{Wx}\sqrt{-2\ln U_1}\sin(2\pi U_2) \quad (2)$$

where: W_{rx} is the wind velocity (month X) randomly generated; μ_{Wx} the average value of the wind velocity (month x); σ_{Wx} is the standard deviation of the wind velocity (month x).

The second component was obtained with the correlation with the randomly generated solar energy. In that case two possibilities exist: when the variation is larger than the obtained with a unity correlation (3) or when the variation is lower (4).

$$W_{cSx} = \frac{(S_{mx} - S_{xM})(2 - \rho_{xS,W})(W_{xM} - W_{xm})}{S_{xM} - S_{xm}} \quad (3)$$

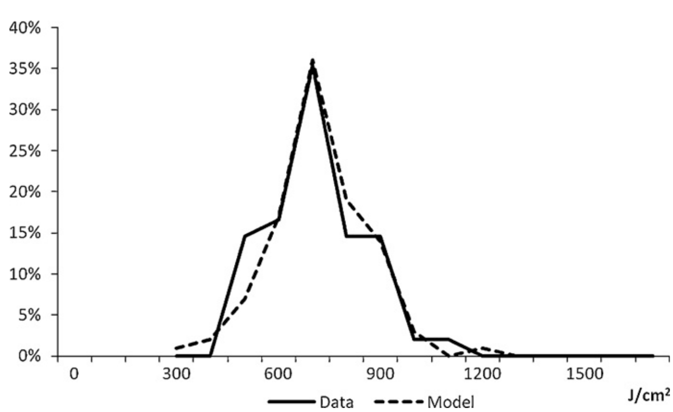


Fig. 1. Distribution of the, average daily, solar radiation, in January.

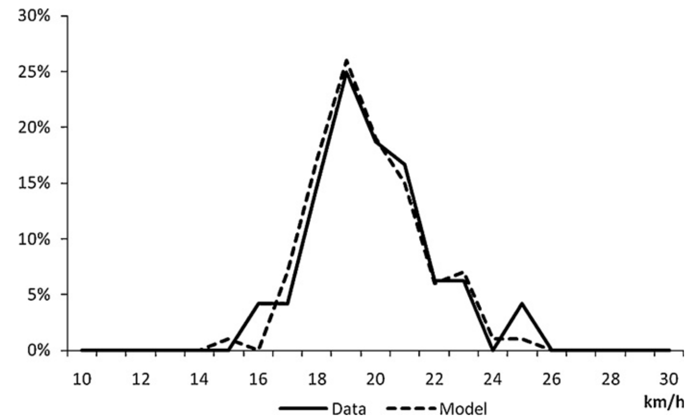


Fig. 2. Distribution of the wind velocity, in January.

$$W_{cSx} = \frac{(S_{mx} - S_{xM})\rho_{xS,W}(W_{xM} - W_{xm})}{S_{xM} - S_{xm}} \quad (4)$$

where: W_{CSx} is the wind velocity (month x) generated with the correlation with solar radiation; $\rho_{XS,W}$ the correlation between the solar radiation and the wind velocity (month x); W_{xM}, W_{xm} is the maximum and minimum wind velocity (month x); S_{xM}, S_{xm} is the maximum and minimum solar radiation (month x).

The final value is the addition of the correlated value weighed by the correlation and the random value weighed by one minus the correlation value (5).

$$W_{mx} = W_{cSx} \cdot \rho_{xS,W} - W_{rx}(1 - \rho_{xS,W}) \quad (5)$$

where W_{mx} is the wind velocity of the model (month x).

The water inflow is the most uncertain variable and has a different distribution (Fig. 3). Due to such shape, a normal distribution generation cannot be used. For each month the data was divided in intervals and for each interval a number of random values proportional to the probability distribution were generated.

Due to the larger uncertainty, both the correlations with the solar radiation and wind velocity were used. The final value is the addition of the correlated values weighed by the correlations and the random value weighed by two minus the sum of the correlations (6).

$$H_{mx} = H_{cSx} \cdot \rho_{xS,H} + H_{cWx} \cdot \rho_{xW,H} + H_{rx}(2 - \rho_{xS,H} - \rho_{xW,H}) \quad (6)$$

where: H_{mx} is the hydro inflows of the model (month x); H_{CSx} the hydro inflows (month x) generated with the correlation with solar radiation; $\rho_{XS,H}$ the correlation between the solar radiation and the hydro inflows (month x); H_{CWx} the hydro inflows (month x)

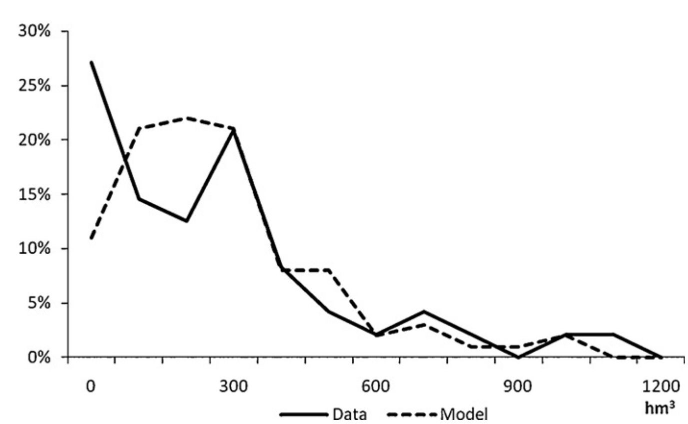


Fig. 3. Distribution of the water inflow, in January.

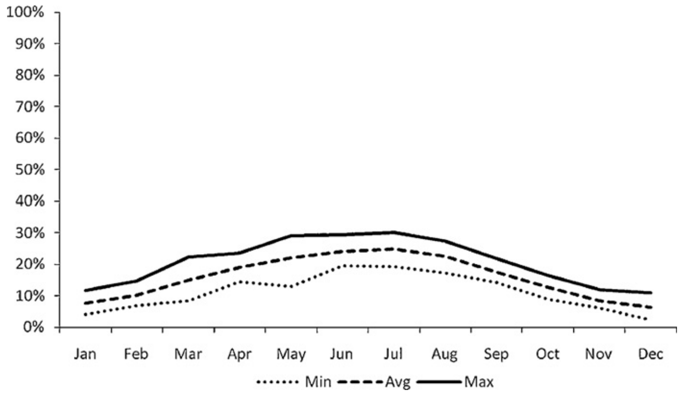


Fig. 4. Monthly variation of the solar capacity factor.

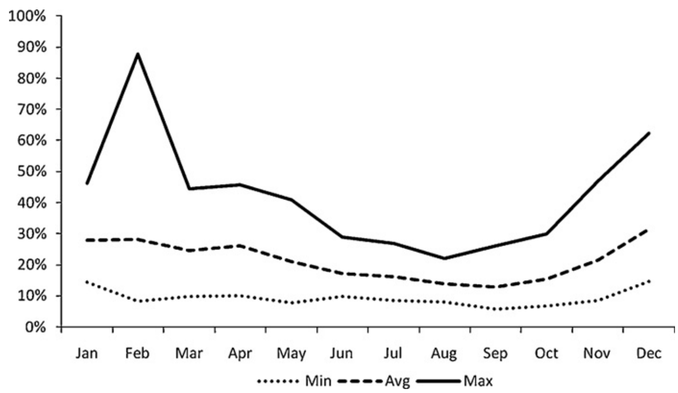


Fig. 5. Monthly variation of the wind capacity factor.

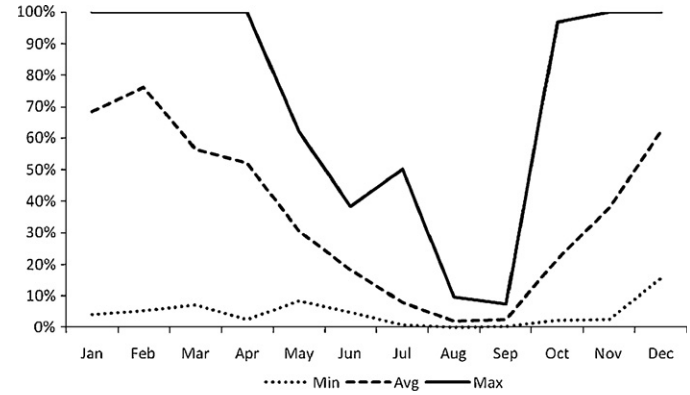


Fig. 6. Monthly variation of the hydro capacity factor.

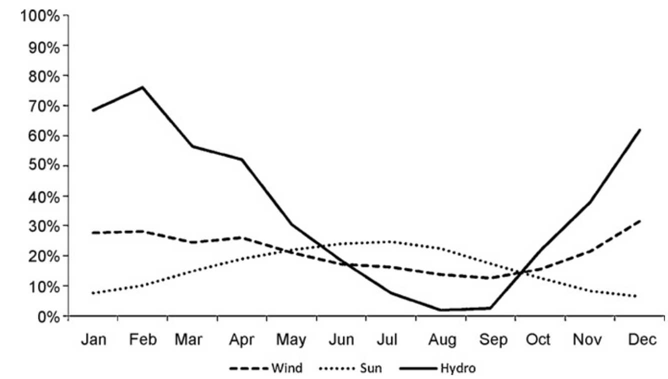


Fig. 7. Yearly variation of the wind, solar and hydro capacity factor.

generated with the correlation with wind velocity; $\rho_{XW,H}$ the correlation between the wind velocity and the hydro inflows (month x); H_{rx} is the hydro inflow (month x) randomly generated.

4.2. Climate data analysis

In a way similar to wind power, hydropower and solar power are also intermittent resources, due to the dependence of meteorological conditions. However the variations do not occur at the same time for the three renewable sources and with a proper mix the total output can partially be compensated [9].

Using the climate model, a series of 500 years was generated for the three variables. The three collected variables have different units of measurement, and thus to enable a comparison between them, a conversion to an undimensional unit was made, the capacity factor. As it can be observed in Fig. 4, the solar radiation has small fluctuations relatively to the average year and additionally the yearly variation curve does not change in shape. For each month the extreme values (Max and Min) are also shown.

The wind velocity presents high variations relatively to the average year, with impact in the yearly variation curve shape (Fig. 5).

The hydro inflow presents huge variations relatively to the average year and unpredictability (Fig. 6) preventing a reliable estimation. Large storage reservoirs can dampen the fluctuations of the water inflows.

Fig. 7 shows the average monthly capacity factor for each variable (wind velocity, solar radiation and water inflow). As it can be observed the solar radiation is higher between May and September, occurring the opposite with the wind velocity and water inflow. Thus, the solar radiation has the maximum value in July and the minimum in December. Both the wind velocity and water inflow has the maximum value in February, registering the minimum in September and August, respectively.

The wind velocity and the water inflow have average variations along the year with a very similar course, having the two curves a high correlation (0.98). The solar radiation varies almost inversely relatively to the wind velocity and the water flow (correlation of −0.7 and −0.66, respectively). That observation indicates that the complementarity between solar energy and the pair wind power/hydropower is quite high. Solar energy can then be used to face the seasonal variations of wind power. The hydropower is not complementary to wind power but due to its similar variations is the ideal means to store the excess wind energy to cope with the intermittence, using its storage, dispatchable power and dynamic response capabilities.

5. Demand-side management

Rather than attempting to match power generation to consumer demand, the philosophy of load management takes action to vary the load to match the power available. Through the proper application of demand-side management (DSM) technologies [10] it is possible to reduce the need of new installed intermittent power to achieve the renewable penetration targets.

The most critical situations due to high penetration of wind power occur in periods with high energy consumption. Thus, the DSM technologies have a major role in avoiding critical situations due to intermittent power, mainly the technologies with impact in the peak load reduction. One serious problem occurs in the summer days with high temperatures (elevated consumption of air conditioning) with reduced wind velocities. Therefore the energy-efficient DSM technologies with high impact in the peak load hours are the most important.

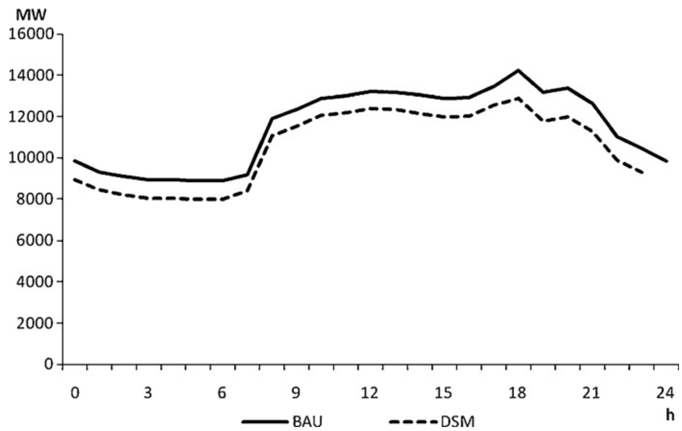


Fig. 8. Impact of the DSM in the Portuguese load diagram (January 2020).

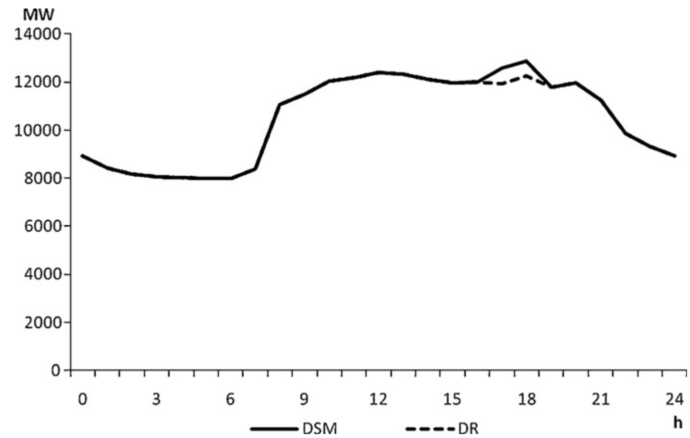


Fig. 9. Impact of the DR in the Portuguese load diagram (January 2020).

Taking as reference the electric energy consumption in Portugal, in the year of 2008, an evaluation of the consumption evolution was made, considering a business-as-usual scenario (BAU) and a scenario with DSM measures application. In such evaluation, a consumption increase of 3%/year (BAU scenario) and the application of DSM measures corresponding to 1% of the year consumption (DSM Scenario) were considered.

A variety of demand-side management technologies were considered to accomplish such objective, trying to achieve a larger impact with a minimal cost. The aggregated impact in the load diagrams of the selected technologies in the residential (lighting, appliances and space conditioning), services (lighting, office equipment and space conditioning) and industrial (lighting, energy efficient motor systems and drives) sectors was determined. As example, Fig. 8 shows the global load diagram (joining the impact of the three sectors), on a work day, in January, to 2020. In such image the largest impact of the DSM measures in the peak load hours can be observed. In this example, a reduction of 8.3% in the peak load was obtained, due to the applied DSM measures, minimizing the most dangerous situations originated by the intermittence of the renewable resources. It must be noted that such impact, caused by the DSM measures, is obtained with an average cost of 0.023 €/kWh, that is much less than the production cost of any renewable energy.

Other technology that can perform a major role in the integration of renewable intermittent power is demand response (DR) [11]. With these technologies it is possible to direct or indirectly force a consumption reduction in critical situations, in a short time. The idea behind DR is that if the marginal peak load price is higher than the value that a consumer gets out of the services derived from the electricity, he would be willing to modify the demand, if paid the peak price or slightly less instead. Traditionally the DR technologies were typically used to attend to economical concerns. However, nowadays they can be used to improve the system reliability, reducing instantaneously the energy consumption to prevent the most unbalanced situations, like the problems that result from the large space conditioning consumption on days with reduced wind velocity. As more customers practice automated price-responsive demand or automatically receive and respond to directions to increase or decrease their electricity use, system loads will be able to respond to, or manage, variability from wind power production.

Additionally to the DSM scenario, controlling 5% of the peak load (nearly 490 MW) with DR technologies it is possible to smooth the loads diagram. In Fig. 9 it is possible to see the impact of the DR measures added to the DSM scenario. With the aggregated action of the measures it will be possible to achieve a peak load reduction, in 2020 of 12.9%.

6. Renewable mix optimization

6.1. Intermittence

The intermittence and complementarity between renewable sources can be divided in two different time scales: between years or between months in an average year. For the intermittence between years, the percentage of the wind, solar and hydro capacity factor, which maximizes the global capacity factor in an average year, must be determined. Also the difference between each year and the average year must be minimized, being such a difference less than 15%, since this is the minimum possible value, based on a 500 year simulation with the existent data (7). The sum of determined percentages must be 100% (8) and each one must be positive (9).

$$\frac{(Ct_S.c\,f_{Sa} + Ct_W.c\,f_{Wa} + Ct_H.c\,f_{Ha})}{(Ct_S.c\,f_{Savg} + Ct_W.c\,f_{Wa} + Ct_H.c\,f_{Havg})} \geq 0.85 \tag{7}$$

$$Ct_S + Ct_W + Ct_H = 1 \tag{8}$$

$$Ct_S, Ct_W, Ct_H \geq 0 \tag{9}$$

Using the climate model, the conditions are tested for a series of 500 generated years to maximize the energy generation objective (10).

$$\max(Ct_S.c\,f_{Savg} + Ct_W.c\,f_{Wavg} + Ct_H.c\,f_{Havg}) \tag{10}$$

where: Ct_W, Ct_S and Ct_H is the contribution of the wind, solar and hydro component; cf_{Wavg}, cf_{Savg} and cf_{Havg} the capacity factor in average year of the wind, solar or hydro component; cf_{Wa}, cf_{Sa} and cf_{Ha} is the capacity factor in the year A (1–500) of the wind, solar or hydro component.

The optimal solution for the above problem has a share of: 44% in wind, 39% in solar and 17% in hydro production.

For the intermittence between months, in an average year, the percentage of the wind, solar and hydro capacity factor, which maximizes the global capacity factor, was determined. Simultaneously, a minimum difference between the global capacity factor and the desired variation to achieve the monthly consumption was searched. Thus, a condition that such difference cannot exceed 23% (again, this is the minimum possible value, based on a simulation with the existent data), in any month of the average year, was set (11). For such analysis the relation between the consumption in each month and the average monthly consumption was considered. Also the determined percentage sum must be 100% (12) and each variable must be positive (13). In the hydropower case, due to

the storage capacity associated with these plants, it was considered that the monthly difference relatively to the annual average can be reduced by 1/3.

$$\frac{(Ct_S.c\,f_{Sb} + Ct_W.c\,f_{Wb} + Ct_H.c\,f_{Hb})}{Ct_{Cb}(Ct_S.c\,f_{Savg} + Ct_W.c\,f_{Wavg} + Ct_H.c\,f_{Havg})} \geq 0.77 \tag{11}$$

$$Ct_S + Ct_W + Ct_H = 1 \tag{12}$$

$$Ct_S, Ct_W, Ct_H \geq 0 \tag{13}$$

Using the climate model, the conditions are tested to a series of 500 generated years to maximize the objective (14).

$$\max(Ct_S.c\,f_{Savg} + Ct_W.c\,f_{Wavg} + Ct_H.c\,f_{Havg}) \tag{14}$$

where: cf_{Wb}, cf_{Sb} and cf_{Hb} is the capacity factor in the month b (1–12) of the wind, solar or hydro component; cf_{Wavg}, cf_{Savg} and cf_{Havg} the average capacity factor of the 12 months of the wind, solar or hydro component; Ct_{Cb} is the percentage of the consumption in the month b (1–12).

The optimal solution for the above problem has a share of: 10% in wind, 65% in solar and 25% in hydro production.

Thus, taking into account the above results, the following conditions must be minimized in the expansion of renewable capacity, in order to ensure minimum intermittence either annually (15) or monthly (16). In such analysis the solar power was divided in photovoltaic and concentrated solar power (CSP) with storage [12].

$$\min[2.56P_{PV} + 2.56P_{CSP} - 1.14P_W - 2.94P_H] \tag{15}$$

$$\min[1.54P_{PV} + 1.54P_{CSP} - 5P_W - 2P_H] \tag{16}$$

where P_{PV}, P_{CSP}, P_W, and P_H are the installed power in photovoltaic, concentrated solar power, wind and hydro power.

6.2. Peak load contribution

In Portugal, taking as a reference the summer and winter peak loads in a BAU scenario, the impact of the DSM and DR measures was considered. The obtained power was weighed by the desirable renewable power energy contribution share and the forecasted contribution of each renewable source was subtracted. In such objective function the use of biomass power was also considered (P_B). Thus, the contribution to the peak load can be optimized by (17), to winter and by (18), to the summer.

$$\min[Ct_R(P_{BAUW} - P_{DSMW} - P_{DRW}) - Ct_{PVW}P_{PV} - Ct_{CSPW}P_{CSP} - Ct_{WW}P_W - Ct_{HW}P_H - Ct_{BW}P_B] \tag{17}$$

$$\min[Ct_R(P_{BAUS} - P_{DSMS} - P_{DRS}) - Ct_{PVS}P_{PV} - Ct_{CSPS}P_{CSP} - Ct_{WS}P_W - Ct_{HS}P_H - Ct_{BS}P_B] \tag{18}$$

where: Ct_R is the renewable power contribution to the global energy production; P_{BAUW}, P_{BAUS}, P_{DSMW}, P_{DSMS}, P_{DRW} and P_{DSR} the peak load in to winter (W) and summer (S) to the BAU, DSM reduction and DR reduction scenarios; Ct_{PVW}, Ct_{PVS}, Ct_{CSPW}, Ct_{CSPS}, Ct_{WW}, Ct_{WS}, Ct_{HW}, Ct_{HS}, Ct_{BW}, Ct_{BS} is the contribution to the winter (W) and summer (S) peak load for each renewable technology.

The contribution of each power generation technology to meet the peak load was forecasted by the interception between the daily capacity factor diagram, for each technology, with the hour of the peak load, for the winter and the summer peaks, taking into account the technologies dispatchability.

6.3. Production costs

To optimize the renewable mix, the production costs need to be minimized (19).

$$\min[C_{PV}P_{PV}\boldsymbol{h}_{PV} + C_{CSP}P_{CSP}\boldsymbol{h}_{CSP} + C_WP_W\boldsymbol{h}_W + C_HP_H\boldsymbol{h}_H + C_BP_B\boldsymbol{h}_B] \tag{19}$$

where: C_{PV}, C_{CSP}, C_W, C_H, C_B is the levelised cost of energy for each renewable energy; h_{PV}, h_{CSP}, h_W, h_H, h_B is the operation hours of each renewable energy at full power.

6.4. Restrictions

In addition to the previous objectives for the renewable mix optimization, several restrictions need to be considered:

- Energy consumption share to be ensured by renewable sources (20).
- Maximum potential for each renewable technology ((21), as example to the wind power).
- Actual installed power for each renewable technology ((21), as example to the wind power).
- Yearly growth to the installed power for each renewable technology ((22), as example to the PV power).

$$P_{PV}\boldsymbol{h}_{PV} + P_{CSP}\boldsymbol{h}_{CSP} + P_W\boldsymbol{h}_W + P_H\boldsymbol{h}_H + P_B\boldsymbol{h}_B = Ct_R(E_{BAU} - E_{DSM}) \tag{20}$$

$$P_{wi} \leq P_w \leq P_{w_p} \tag{21}$$

$$P_{wi} + Cr_R P_{w_p} - P_w \geq 0 \tag{22}$$

where: E_{BAU} is the annual energy consumption for a BAU scenario; E_{BAU} the annual energy consumption reduction due to the DSM measures; P_{Wi} the installed wind power; P_{Wp} the maximum potential in wind power; Cr_R is the yearly maximum growth to the installed power in each renewable technology.

6.5. Global optimization

Taking as base the available climate data, a climate model was constructed to generate random years (Section 4), used to test the conditions to minimize the intermittence between years and months. Taking as a reference the BAU scenario for the energy consumption growth, the impact of DSM and DR measures was added (Section 5), reducing the required energy consumption to be supplied by renewable sources, the non-guaranteed peak load share, and the productions costs. Such conditions will optimize the renewable mix, subject to the renewable potential, the initial installed renewable power capacity, the maximum renewable capacity yearly growth and the target percentage consumption that needs to be ensured by renewable energies (Fig. 10).

The multi-objective model of the renewable mix optimization have as optimization functions the Eqs. (15)–(19), and as restrictions the Eqs. (20) and (21) (example for wind power) and (22) (example for wind power). Using the described model, a simulation of the years between 2010 and 2030 (with a 5 years interval) was performed for the Portuguese data, considering an increasing renewable share in the total energy production, from 40% in 2010 to 60% in 2030. For the optimization process, a weight of 50% for the costs component and 50% for the reliability component was used. The reliability component was equally divided between the 4 components (intermittence between years,

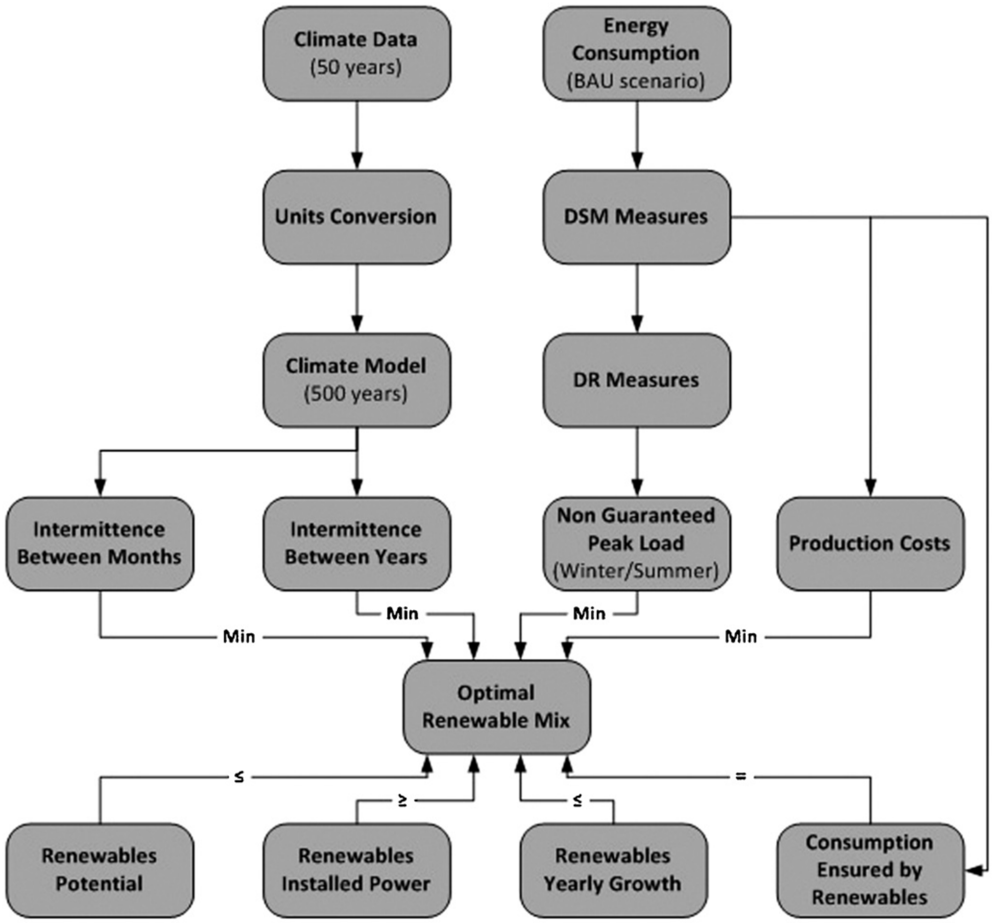


Fig. 10. Multi-objective model.

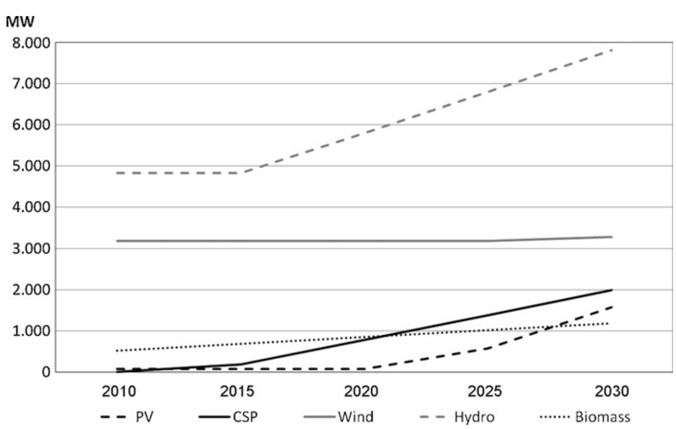


Fig. 11. Optimized Portuguese renewable mix between 2010 and 2030.

intermittence between months, contribution to the winter peak load and contribution to the summer peak load).

Fig. 11 shows the results of the multi-objective model. In the above simulation time period, the obtained results for the objective functions were in the direction of an increasing reliability, due to the reduction of the intermittence (between years and months) and of the non-guaranteed peak load share (winter and summer). In the case of the peak load, the non-guaranteed part was reduced to 34%, for the summer and 32% for the winter. Such evolution was obtained in first place due to the use of dispatchable technologies (biomass, concentrated solar power with storage and hydropower) and after that due to the use of technologies with high complementarity with the wind power (photovoltaic and concentrated solar power).

7. Conclusions

To face the intermittence of renewable sources several options can be considered. The option to mix complementary energy sources like wind power, solar power and hydropower will mitigate the problems, when comparing with only using one source of renewable energy and the use of dispatchable renewable sources has a great importance. Using historic data for the wind, solar and hydro availability a multi-objective model can be used to support such analysis, in order to optimize the complementarity between renewable sources.

DSM and DR can also have a major role, either by reducing the needs of new intermittent capacity or by adjusting the consumption in real time, to face production variations. Thus the demand consumption reduction due to the application of those technologies should be incorporated in the analysis.

The described multi-objective model enables the optimization of the renewable mix, ensuring a minimum level of intermittence (between years and months), a minimum non-guaranteed peak load share (both in summer and in winter) and a minimum global cost, using the complementarity between renewable sources and the cost-effective impact of DSM and DR measures.

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